BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B69 05091

SUBJECT: Preliminary Survey of the Potential for Satellite Servicing - Case 730

DATE: May 22, 1969

FROM: H. B. Bosch

MEMORANDUM FOR FILE

I. INTRODUCTION

One of the likely benefits of an expanded manned spaceflight program is that man's presence in earth orbit might enhance the mission of unmanned satellites. However, to continue with a manned spaceflight program merely to support and attend earth orbiting satellites cannot be justified. Instead, we must consider the general development of manned and unmanned programs in an integrated manner, bearing in mind the possible benefits each may derive from the other.

The term "satellite servicing" in this report means any operation which is performed in orbit on an unmanned satellite to support or enhance its mission. Such an operation could be scheduled (e.g. to replenish expended supplies or to replace obsolete instruments) or unscheduled (e.g. to repair a failed component or subsystem). For a discussion of such servicing operations see Reference 1.

This survey was undertaken in an attempt to answer the following questions:

(a) How many satellites are expected to be in earth orbit around 1980?

(b) What types of orbit will they occupy?

(c) What will be the dollar value represented by these satellites?

(d) What kind of servicing might they require?

(e) What possible economic and other benefits might be derived from manned maintenance of these satellites?

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ABSTRACT

[redacted]

The number and nature of unmanned earth orbiting satellites circa 1980 was estimated in order to assess the potential need for and benefit from servicing satellites in orbit. Based on an annual launch rate comparable to the current one, 80 to 100 active earth satellites are predicted, of which approximately 15 per year can be expected to require some kind of servicing to extend their useful life. The average active lifetime of satellites is projected to be four to five years. Assuming the existence of a space station and a transportation system of relatively low cost, the marginal cost of servicing operational spacecraft appears to be competitive with the cost of replacing them.

Some of these questions cannot be completely answered here, however, for they lead to further questions. For example, assuming an accelerating science-and-applications satellite program, will the trend be toward a greater number of relatively small and simple satellites, or toward larger and more complex, but fewer spacecraft? With the presence of a space station, would it be possible (or even desirable) to integrate sensors with the space station or would they have to continue to be autonomous satellites? How would the complexity of spacecraft design be affected to accommodate manned servicing? The presence of a satellite servicing capability has a direct bearing on the answers to these questions which, in turn, affect the above stated five questions.

Therefore, a reasonable approach is to first assess the potential for satellite servicing based on current knowledge and planning. A "second iteration" study can then address the problem in greater detail. It is in this sense that this study is a preliminary survey.

II. TRAFFIC MODEL

1. Present Satellite Traffic

In February, 1969, the population of active satellites in earth orbit stood at 45. By active is meant any satellite currently receiving commands or telemetering data. These satellites, which are indicated on Table I, are comprised of those supported by STADAN* (Ref. 2) -- except AIMP* -D and E whose orbits are not considered as earth orbits -- plus four INTELSATs*, which are not supported by STADAN. Table I shows that 23 of these (the four DoD, 10 space physics, seven international and two geodesy satellites) are small space and earth science satellites. Acceleration in the applications program can be expected to reduce the ratio of scientific satellites to the total number of spacecraft in orbit, as will be mentioned later.

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*STADAN: Space Tracking And Data Acquisition Network

AIMP: Anchored Interplanetary Monitoring Platform

INTELSAT: INternational TELecommunications SATellite

Note that this count of 45 does not include satellites with classified payloads or other Defense Department satellites not supported by STADAN.

2. Projected NASA Spacecraft

A survey was conducted recently by the Advanced Development Division, GSFC, of all spacecraft projects which are active, committed, or projected (Ref. 3).

Results of this survey are shown on Table II. This tabulation does not include INTELSATs, operational meteorology satellites, or nonmilitary Defense Department satellites (e.g. DODGE*, ERS*). Based on this information, the number of spacecraft can be projected as shown on Figure 1. Here we note the fairly steady continuation of committed, unmanned spaceflight projects through 1973. Then there appears an increase, reflecting some of the current desires in planning. However, the last three years of the decade show a definite drop in spaceflight activity due to a lack of knowledge or planning information. Therefore, this is not a valid way to anticipate satellite traffic around 1980 and beyond.

3. Traffic Predictions

One can construct a reasonable model, though, with which to predict numbers of satellites (without regard to type of satellite) as shown in Figure 2 (Ref. 3). The fundamental assumption here is that the launch rate will continue at its present level of 21 launches per year. This is a reasonable assumption considering past and committed launch activity.

Satellite average lifetimes -- here defined as the length of time a satellite is active in the sense of requiring command and telemetry support -- can be extrapolated as shown on Figure 2. Assuming an additional year of lifetime for each six calendar years yields the solid line on Figure 2, or one additional year of lifetime each four calendar years, the dashed line. This extrapolation gives average lifetimes of four to five years in 1980, which is consistent with current planning (see Section V).

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*DODGE: Department Of Defense Gravity Experiment

ERS: Environmental Research Satellite

This model, therefore, predicts approximately 80 active spacecraft in 1980. This number can be expected to increase further as a result of new activity in the areas of domestic communication and navigation/traffic control. Thus, we can anticipate between 80 and 100 active satellites in 1980.

As mentioned earlier, the above surveys did not include any military or classified satellites. We note only that such an inclusion could easily double the number of active satellites.

III. ORBIT SELECTION

1. Present Distribution of Orbits

The orbits of the presently active 45 satellites (see Section II.1) are shown in Figure 3. The eccentric orbits appear as vertical lines which range from the perigee to the apogee altitude. Almost all orbits between 20° and 100° inclination (especially the highly eccentric ones) are occupied by small, Explorer-type scientific satellites.

The six active meteorology satellites (one Nimbus and five ESSAs*) are in sun-locked orbits; and geostationary orbit (0° @ 36,000 km) is occupied by four INTELSATs and two ATSs*.

Plotting numbers of satellites versus orbit inclination (Figure 4) shows the clustering around equatorial orbits (0° to 10°), near-polar orbits (80° to 90°), and in sun-locked orbits (100° to 110°). The remainder of orbit inclinations are occupied fairly uniformly with the exception of medium inclinations (30° to 40°). These orbits are occupied by our heaviest spacecraft -- three OSOs* and one OAO* (35° @ 770 km). The concentration of weight in these orbits is indicated in Figure 5 by the peak around 35°. Comparison of Figures 4 and 5 shows that the five satellites (11% by number) around that inclination represent 28% of the total weight in earth orbit. This apparently reflects a constraint due to launch vehicle capability for relatively heavy satellites and/or range safety.

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*ESSA: Environmental Survey SAtellite

ATS: Applications Technology Satellite

OSO: Orbiting Solar Observatory

OAO: Orbiting Astronomical Observatory

2. Orbit Selection for the Future

An examination of orbit selection criteria (see Appendix) without regard to the above mentioned launch constraints shows the types of orbits that would be desirable for future earth satellites (Table V). Again, a rather high concentration can be anticipated in geostationary orbit and another in the sun-locked orbits. A few specialized spacecraft can be expected in low altitude, with the highly eccentric orbits occupied by physics satellites. This situation is similar to the present one except that the number ratio of operational applications spacecraft to science satellites is expected to increase significantly in the future.

It is important to recognize that, whereas there is only one geostationary orbit, there is an infinity of sun-locked orbits, even at the same altitude and inclination: whereas two satellites in geostationary orbit are separated only by an in-orbit phase angle, two satellites in equal-altitude polar orbits can move in planes separated by as much as 180° -- depending on the positions of their respective ascending nodes. This is an essential difference which can be an important consideration in selecting orbits for the placement of space stations.

IV. SPACECRAFT VALUES

The list in Table III is typical of present and anticipated earth-orbiting spacecraft. It is not intended as complete. The replacement values shown represent the approximate cost of manufacturing one additional spacecraft with all its subsystems and sensors, then integrating, checking out and delivering it. The launch costs represent the launch vehicle, the launch operation itself and all associated ground support activities. These costs are, of course, based on current technology.

Typical replacement values thus range from the relatively inexpensive $2.7 million TOS* to the OAO costing $50 million or more.. The very expensive ASTRA* and NASO* are defined to be man-attended spacecraft, if not manned. The ERTS* (prototype for operational

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*TOS: Tiros Operational Satellite

ASTRA: Astronomical Space Telescope Research Assembly

NASO: National Astronomical Space Observatory

ERTS: Earth Resources Technology Satellite earth resources satellites) would be valued around $15 million or $25 million, depending on whether the basic spacecraft will be of the OGO*-type or Nimbus-type, respectively.

Another way of representing the investment in satellites would be to list their weights in orbit. Here again we are faced with a lack of knowledge or information on the number and specific types of spacecraft to be orbiting in 1980 (see Section II.2 and Figure 1). The Astronomy Missions Board, for example, has recommended development of a "Heavy Explorer" whose payload package might weigh 24,000 pounds. The spacecraft weight could be two tons or more. The Earth Survey Panel of the Planning Steering Group is considering a system of three geostationary and three sun-synchronous satellites carrying a combined payload of around 30,000 pounds. These considerations are very tentative and although they are not definitive, they do indicate a trend to heavier spacecraft.

Assuming that the active satellite population will at least double in the next decade (see Figure 2), and in view of the apparent trend toward heavier spacecraft, a rough estimate of the total weight in orbit might be of the order of 100,000 pounds. However, it is presently not possible to give any usable estimate of the distribution of this weight, analogous to that which is shown on Figure 5.

V. SATELLITE LIFETIMES

The actual lifetime of a satellite -- or the period of time during which it will remain active -- is difficult to predict. Examining historical data shows that the ESSAs (same as TOS), for example, are "designed" for three to six months, in the sense that any ESSA which remains active for at least three months is considered to have fulfilled its intended mission. Yet ESSA-2, for example, is now more than three years old. Earlybird (INTELSAT I) had a design lifetime of 18 months. Yet, after 42 months of successful operation, it was turned off and replaced by the newer and more economical INTELSAT II satellites. These have design lifetimes of three years. The current INTELSAT IIIs are designed for five years operation and INTELSAT IVs will be designed for seven years. This at least indicates a rapid increase in the reliability of operational satellite design and it is compatible with the average lifetime of around five years for 1980 as shown on Figure 2.

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*OGO: Orbiting Geophysical Observatory

The useful lifetime of a satellite may be limited by components which deteriorate as a matter of course due to aging, such as video tubes. For example, experience has shown that solar cell degradation due to electron bombardment can cause a power degradation of around 8 - 10% per year in geosynchronous orbit (Ref. 4). Also, the thermal reflective coating on the OAO-II deteriorates due to ultraviolet radiation from the sun. Flight experience thus far has shown that the absorbtance of the coating has increased from 15% at launch to 24%, whereas the emittance has remained at 75%.

The orbits of some spacecraft, such as communication satellites, have to be maintained or updated to a certain degree of precision. Thus, the amount of station-keeping propellant onboard can place an upper limit on useful lifetime.

The lifetime of batteries is primarily determined by the number of charge-discharge cycles. Therefore, in a low-altitude orbit, where occultation by earth occurs relatively frequently, batteries constitute a more severe lifetime limit than in a geosynchronous orbit.

Obsolescence is a less obvious, but equally important factor determining useful lifetime. This is primarily a matter of economics in the sense that, after a certain number of years, it may become very inefficient to continue operating a satellite. Determining an obsolescence period requires an extensive analysis of the economics of operating an entire system of which the satellite is only one component.

A satellite's usefulness can also be reduced or ended by a random failure of a subsystem, this being related to the reliability of the design. These events, of course, are much less predictable. The most frequent failures on meteorological satellites, for example, have been mechanical failures of tape recorders and camera shutters. Tape recorders may eventually not be needed with the development of a data relay satellite system (see Appendix) and cameras on meteorology satellites may soon be replaced by scanning radiometers. What problems such advanced systems will introduce cannot be determined now.

Finally, the traffic model mentioned in Section II.3 (Figure 2) can give an estimate of the annual rate of satellite terminations as shown in Table IV. Assuming that the present number of small scientific and technology satellites will remain essentially the same for the next decade and that the increase in the total number will be primarily in operational applications spacecraft, we can estimate that approximately 75% of the annual terminations will involve operational spacecraft. Thus, around 12 to 15 satellites can be expected each year to require servicing in order to extend their useful life.

VI. SERVICING CONSIDERATIONS

As it was defined earlier, the term "satellite servicing" means any operation which is performed in orbit on an unmanned satellite to support or enhance its mission (see Section I). In this context, earth orbiting spacecraft can be categorized by the effect such servicing might have on their mission. We define four categories as follows:

First, there are those spacecraft for which manned servicing is required by definition. These are the large astronomy and physics facilities such as ASTRA and NASO.

Second, there are those which appear likely to benefit from manned servicing or attendance. In this category would be the large, operational systems of earth resources satellites; medium sized and special purpose astronomy satellites such as OAO and OSO; direct broadcast satellites; as well as applications and technology satellites (ATS).

Third, there are those spacecraft for which there is no apparent need for manned attendance, but where servicing might show economical benefit. These would be operational satellites such as INTELSAT and ESSA which, due to their long lifetime and increasing reliability, appear to perform their missions quite successfully.

Fourth is the category for which servicing is essentially infeasible. For example, the Explorer-type physics satellites are in highly eccentric orbits and therefore require large amounts of energy to capture or rendezvous with. They are also small enough to be replaced and launched relatively inexpensively. Also in this last category would be the short duration (three to 30 days) biosatellites, which are intended to be re-entered at the conclusion of their respective missions.

The subject of short duration biomedical experiments in orbit, however, raises a further question (see Section I): Certainly, the biosatellites as they are currently envisioned fall in the fourth category. But, with the existence of a low cost transportation system and with scheduled shuttle trips from earth to orbit and back, it might become desirable to construct a large, permanent facility in orbit to be visited for installing, monitoring, or removing experiments. Such tradeoff considerations in several satellite disciplines could reduce the number of satellites estimated in Section II.3, at the same time increasing servicing traffic.

The concept of a satellite's "end of life" also requires further study. The period of time during which a satellite requires tracking and command support, and during which it is capable of providing usable telemetry, is difficult to define a priori. The failure of a critical component (e.g. a battery) can terminate the useful life of a system. If it is possible to repair or replace this component, the system can be restored to usefulness. Past a certain point in time, however, it may become more desirable to replace the entire satellite rather than repair or update it. This is the obsolescence period mentioned in Section V.

On the other hand, an existing servicing capability can enable the continuous updating of a satellite by replacement of degraded or obsolete components or sensors. In this way delays due to the building, integration, checkout, and launch of a new spacecraft can be avoided and technological innovations made operational with a minimum of delay.

VII. SERVICING COST

For the purposes of this survey we shall assume that there is at least one space station in orbit which is already operating for reasons other than satellite servicing. We assume the existence of an accompanying transportation system of relatively low cost, as well as regularly scheduled shuttle flights between earth and the space station(s). We also assume the availability of a fully paid-for inter-orbital vehicle which can be used for satellite servicing. In this context we can consider the cost of satellite servicing as marginal. For simplicity we will not deal with the question of personnel cost allocation. Thus, the marginal cost of servicing a satellite will be represented by the cost of bringing from earth into orbit the propellant required by the service vehicle. *This represents the most favorable possible cost model for satellite servicing.*

Two modes of servicing an orbiting spacecraft from a space station are considered as follows:

1. in situ servicing, requiring one roundtrip: the service vehicle goes from the space station to the satellite; the required maintenance operations are performed; and the service vehicle returns to the station.

2. servicing at the space station, requiring two roundtrips: the service vehicle goes out and retrieves the satellite to the space station. After maintenance has been performed, the service vehicle is refueled and goes out once again to replace the satellite to its original orbit, and then returns to the station.

Three vehicles are considered as representative of the type of vehicle which might be used for satellite servicing, assuming they are already at the space station. These vehicles are:

1. a small tug, using space storable propellants, which is sized to execute a 10° plane change in a 250 nm circular orbit to retrieve a 5,000 pound satellite, while carrying a 2,500 pound service module which can hold one or two men.

2. a logistics vehicle, similar to Lockheed's Star Clipper without the disposable tanks, and

3. a large, cryogenic tug, which is sized to retrieve a 5,000 pound satellite in geosynchronous orbit from a coplanar, 250 nm circular orbit, while carrying a 2,500 pound service module.

The dry weight* (W_d), propellant capacity (W_p), and specific impulse (I_s), as used for these three vehicles in this report, are:

space storable tug:	W_d = 3,150 lbs.
	W_p = 7,500 lbs
	I_s = 310 sec.
logistics vehicle:	W_d = 41,000 lbs.

*structure, tanks, engine, service module.

W_p = 59,000 lbs.
I_s = 460 sec.

cryogenic tug: W_d = 7,900 lbs.
W_p = 55,000 lbs.
I_s = 460 sec.

Figure 6 shows constant-ΔV contours representing impulsive transfer maneuvers between a 250 nm circular orbit and other circular orbits, the plane-change impulse occuring at the apogee of the transfer ellipse. Thus, the design mission for the space storable tug corresponds to a oneway characteristic velocity of $\Delta V \approx 4{,}000$ fps, and that for the cryogenic tug corresponds to a oneway characteristic velocity of $\Delta V \approx 13{,}000$ fps. Figure 6 shows that the space storable tug is also capable of an inplane transfer to and from a 1,800 nm circular orbit; and that the cryogenic tug is also capable of a roundtrip mission consisting of a pure plane change of 32° at 250 nm.

The amount of propellant required for satellite servicing by each of the above vehicles is shown in Figures 7, 8, and 9. Any mission, whether it be servicing at the space station or in situ, can be defined by that ΔV which characterizes the oneway transfer between the space station orbit and the orbit of the satellite to be serviced.

For example, the oneway characteristic velocity for servicing a satellite in a 750 nm, 100° orbit from a polar space station at 250 nm is approximately 5,400 fps. Working on such a satellite in situ, using the space storable tug (Fig. 7), requires 6,000 lb propellant. If the satellite weighs 1,000 lb, servicing it at the space station and then returning it to its original orbit requires a total of 14,000 lb propellant. Assuming that a marginal cost of $100 per pound of propellant delivered to low earth orbit is feasible in 1980, this means that the marginal cost of servicing such a satellite is $1.4 million or less. This compares favorably with the present replacement value of meteorology satellites - $2.7 million or more.

If the logistics vehicle (Fig. 8) were used for servicing the same satellite in situ and at the space station, the amounts of propellant required would be 43,000 lb and 88,000 lb, respectively. On this basis the space storable tug is obviously more economical. However, the logistics vehicle has the advantage of a larger volume which could be used as a hangar or as room for a team of specialists.

For another example, the characteristic velocity for servicing a satellite in geostationary orbit from a space station at 250 nm and 30° is approximately 14,000 fps. If such a satellite is to be serviced in situ, the cryogenic tug (Fig. 9) requires 45,000 lbs propellant. At $100 per pound of propellant, the marginal cost of repairing this satellite is $4.5 million. This also compares favorably with the current estimate of the replacement value for a communication satellite - $8 million. The servicing cost would be reduced considerably by the presence of a space station is geostationary orbit.

These results should be considered quite tentative, however. Design studies are needed to obtain better estimates of the dry weight of a space tug, which has a strong impact on the amount of propellant required. In addition, the future cost per pound of bringing propellant into orbit is quite uncertain at this time.

VIII. SUMMARY

Assuming that the annual launch rate over the next decade will be essentially the same as the present rate, the unmanned satellite population in 1980 is projected at 80 - 100. This uncertainty depends mainly on developments in domestic communication and navigation/traffic control satellite systems. The inclusion of military satellites in this estimate could easily double the population.

A potentially large concentration of relatively simple and long lived communication, navigation and air traffic control satellites, as well as larger data relay and earth applications spacecraft, can be expected to occupy geostationary orbit. Similarly, a concentration of small and medium, earth observing, operational satellites can be expected in sun-synchronous and other near polar, low altitude orbits. The small, space science satellites will remain in special orbits of high eccentricity and various inclinations, as they are today.

The major astronomy and space physics facilities will, by definition, require man's attendance. The medium and small, operational spacecraft will likely benefit from servicing. However, servicing the small, space science satellites appears impractical.

Assuming the existence of at least one space station, together with a relatively low cost transportation system (earth-to-orbit logistics vehicles and interorbital service tugs), the marginal cost of servicing even small operational satellites could be competitive with the cost of replacing them.

Although the economic feasibility of satellite servicing has been examined in this survey on a marginal cost basis, the desirability and extent of man-attendance remains to be studied from other aspects.

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Attachments
  Acknowledgment
  Appendix
  References
  Tables I-V
  Figures 1-9

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APPENDIX

Some general criteria for selecting altitude and orbit inclination for various earth satellite missions (see Table V) are listed below. These criteria are only mission oriented and do not reflect launch vehicle or range safety constraints.

Astronomy

At low altitude an optical astronomy mission would suffer from infrared radiation from the earth and from light scattered off the atmosphere. In the region of the Van Allen belts, intense particle bombardment can cause damage. A geostationary orbit (an equatorial, circular orbit with a period of one day whose ground trace, therefore, is a stationary point on the equator) has the advantage of being far from the earth and of being in continuous communication with a selected ground station.

For solar astronomy, a sun locked (or sun synchronous) orbit would be advantageous. This is a circular orbit whose altitude and inclination are such that the ascending node regresses at the same rate as the sun's apparent annual motion, thus keeping the orbit plane orientation "locked" relative to the earth-sun line throughout the year. A sun locked orbit can be chosen to be in sunlight continuously thereby not only affording continuous viewing of the sun and continuous power generation by solar cells, but also avoiding thermal cycling. Earth occultation in geostationary orbit, however, is minimal over a year.

For an X-ray or Gamma-ray astronomy mission, a low altitude orbit has the advantage that the Van Allen belts shield the orbit from solar wind particles (which not only degrade instruments but also are a source of "noise") whereas their effect on electromagnetic radiation is imperceptible. However, the extent of the South Atlantic Anomaly (an earthward bulge in the inner Van Allen belt) is such that only a nearly equatorial orbit can avoid eventually drifting through it. Therefore a low altitude astronomy orbit should also be of very low inclination.

Communication

A communication satellite in geostationary orbit, especially for point-to-point communication, gives the advantage that ground antennas pointing at it do not have to be slewed; also communication contact can be maintained continuously. A geostationary orbit is generally desirable for communication satellites although other orbits have also been used under special circumstances, such as for the Soviet Molniya satellites (12 hour elliptic orbits at 65° inclination) and the Defense Department IDCSP* (intentionally imprecise, nearly geosynchronous orbits).

Earth Resources

An earth observing spacecraft which needs high resolution must orbit at low altitude. Frequency of coverage, or ground track repetition rate, depends on orbit period which is determined directly by orbit altitude.

If coverage is to include the continental U.S., the orbit inclination should be at least 50°. To include most of Europe 60° will suffice, and a 70° inclination will cover most of the populated globe.

Ground illumination is also an important criterion. For geology, for example, a relatively low sun angle is desirable. For agriculture (e.g. observing the seasonal progress of a wheat field) it is important that a sequence of observations be made under the same lighting conditions. Thus, sun locked orbits appear to fulfill most of the criteria for earth resources satellites.

Meteorology

To observe local meteorological phenomena, again a low orbit is desirable. However, a minimum altitude is determined by a requirement for continuous coverage (e.g. a 10% overlap of photographs to facilitate composition of a mosaic). High inclination is required for global coverage. For local meteorology, as in the case of agriculture, it is important that passage over any given area always occur at the same local time. Thus, appropriately selected sun locked orbits are necessary.

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*IDCSP: Initial Defense Communication System Program

Satellites in geostationary orbit are also required for synoptic meteorology and for observing large scale phenomena such as the formation of hurricanes.

Navigation and Traffic Control

Most proposals for such systems (Ref. 5) call for at least three satellites in geostationary orbit, thus achieving almost global visibility. A few systems (Ref. 6) also include satellites in geosynchronous (one-day period) orbits which are elliptic and/or inclined to the equator. The reason is as follows: The ground track of a one-day, equatorial, circular orbit is a stationary point on the equator; if this orbit were made elliptic, its ground track would be a line segment along the equator. On the other hand, if the original circular orbit were inclined to the equator, its ground track would resemble a figure eight moving north-south across the equator. The right combination of ellipticity and inclination can then be chosen so that the resulting ground track is a circle centered on the original point on the equator. A system using such satellites yields high precision navigation data (Ref. 7). One system would even include three geosynchronous (one-day period) satellites in polar orbit (Ref. 8).

Oceanography

In oceanography it might be desirable to select an orbit for a special purpose, such as observing the Atlantic and Pacific tuna regions. A low altitude orbit of inclination around 50° would fill the needs of such a mission. At the same time, as in the case of meteorology, a geostationary orbit is required for synoptic observations.

Physics

Most of the physics satellites are in orbits of very high eccentricity so that they can take measurements as they pass through the various "layers" of the ionosphere, through the magnetopause, and into interplanetary plasma. Other significant orbital parameters are the orientation of the line of apsides and the orbital inclination relative to the plane of the ecliptic. Depending on what they are to measure, some satellites stay close to the ecliptic plane while others move perpendicular to it. Such orbits are sensitive to perturbations from lunar and solar gravitation. Therefore most space physics satellites will be in highly eccentric orbits of almost any inclination (referred to the equatorial plane).

Tracking and Data Relay

The purpose of such a satellite system is to provide full time "coverage" of all earth satellites in relatively low altitude (3,000 km or less) orbits. Unconstrained, realtime tracking coverage is important at orbit insertion and for possible variable-orbit satellites. Also, realtime command and data relay eliminates the need for tape recorders and frees the selection of orbits from constraints due to the location of ground stations. The geometry of a geostationary orbit is such that a minimal system of two tracking and data relay satellites placed 180° apart can provide the desired coverage.

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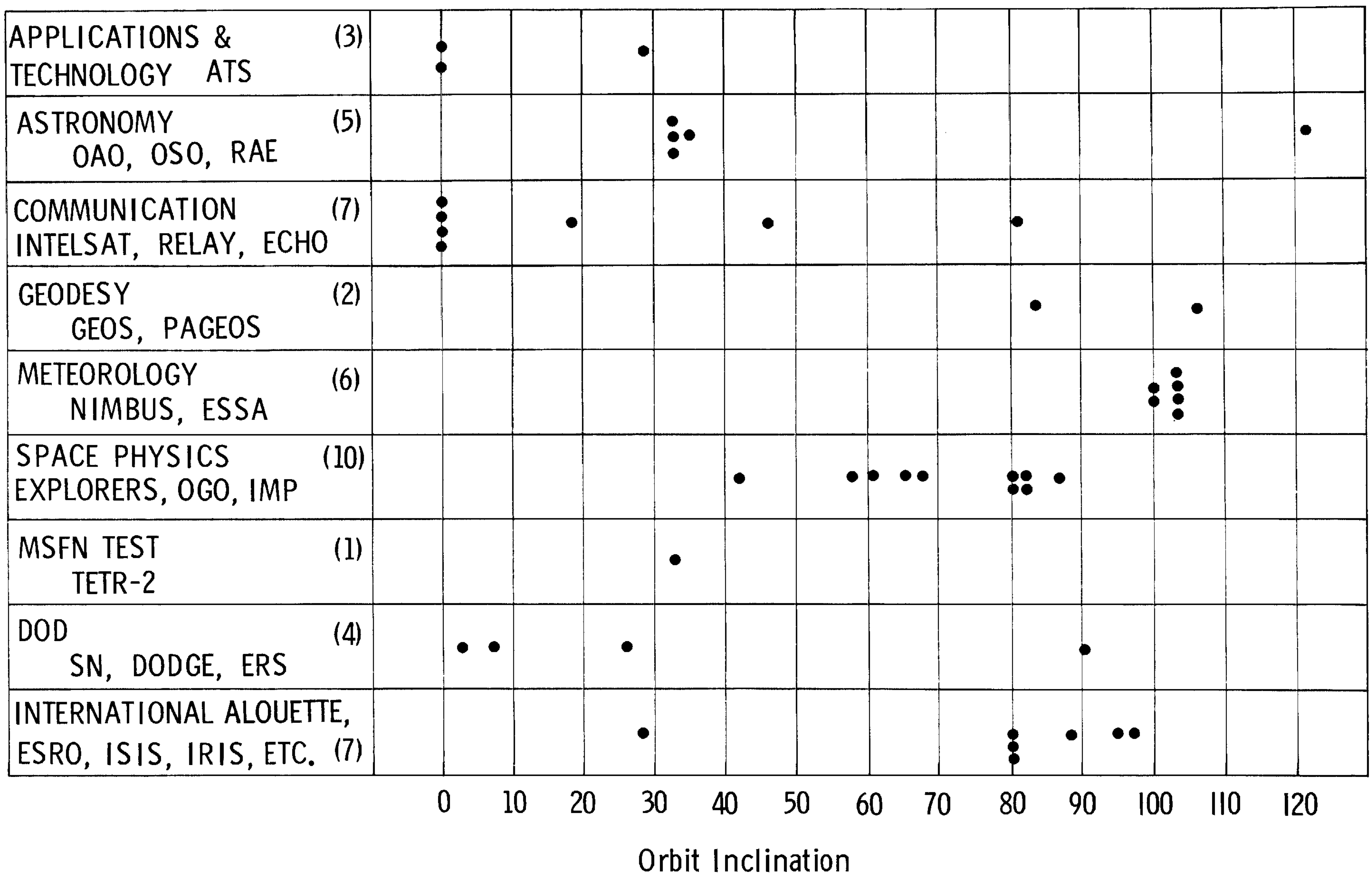

Table I. Current (February 1969) Distribution of 45 Earth Satellites by Mission and Inclination.

UNMANNED AUTOMATED SPACECRAFT MISSION MODEL

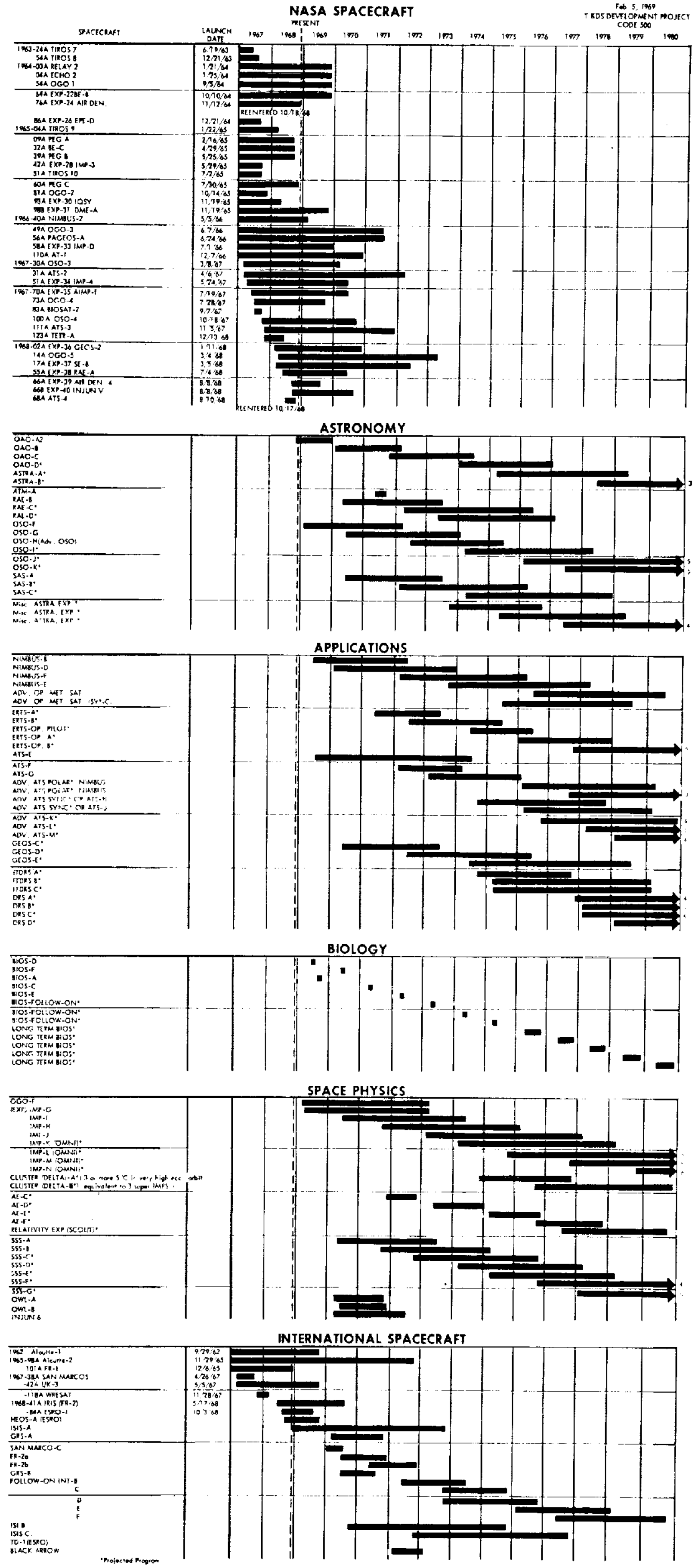

Table II.

DISCIPLINE	SPACECRAFT & APPROXIMATE CURRENT REPLACEMENT VALUE		LAUNCH VEHICLE & LAUNCH COST	
ASTRONOMY	SAS	$ 10 M	SCOUT	$ 2 M
	RAE	$ 15 M	DELTA	$ 4 M
	OSO	$ 15 M	TAT/I DELTA/FW4	
	OAO	$ 50 M	ATLAS/CENTAUR	$ 12-15 M
	*ASTRA	$ 100 M	ATLAS/CENTAUR	$ 12-15 M
	*NASO	$ 1,000 M	SAT IB/TIIIM (?)	> $ 25 M
COMMUNICATION	INTELSAT IV	$ 8 M	TIIIB/AGENA	
			OR ATLAS/CENTAUR	$ 12-15 M
	**TV BROADCAST	$ 15 M	TIIIC	$ 16-20 M
EARTH RESOURCES	ERTS: OGO-TYPE	$ 15 M	DELTA	$ 4 M
	NIMBUS-TYPE	$ 25 M		
METEOROLOGY	TOS	$ 2.7 M	DELTA	$ 4 M
	TOS-M	$ 5 M		

*CONCEIVED AS MAN-ATTENDED

**TO GROUND DISTRIBUTION STATION

Table III. Selected Spacecraft Values.

SATELLITES LAUNCHED PER YEAR	YEARS OF LIFETIME ADDED EACH CALENDAR YEAR	SATELLITES TERMINATED PER YEAR
21	1/6	18
	1/4	16.8
25	1/6	21.4
	1/4	20

Table IV. Annual Rate of Satellite Terminations.

ORBIT TYPE / ACTIVITY	GEOSTATIONARY	GEOSYNCHRONOUS ECCENTRIC &/OR INCLINED	GEOSYNCHRONOUS POLAR	LOW ALTITUDE LOW INCL.	LOW ALTITUDE HIGH INCL.	SUN LOCKED	HIGHLY ECCENTRIC
ASTRONOMY							
COMMUNICATION							
EARTH RESOURCES							
METEOROLOGY							
NAVIGATION & TRAFFIC CONTROL		?	?				
OCEANOGRAPHY							
PHYSICS							
TRACKING & DATA RELAY							

Table V. Some Types of Desirable Earth Orbits.

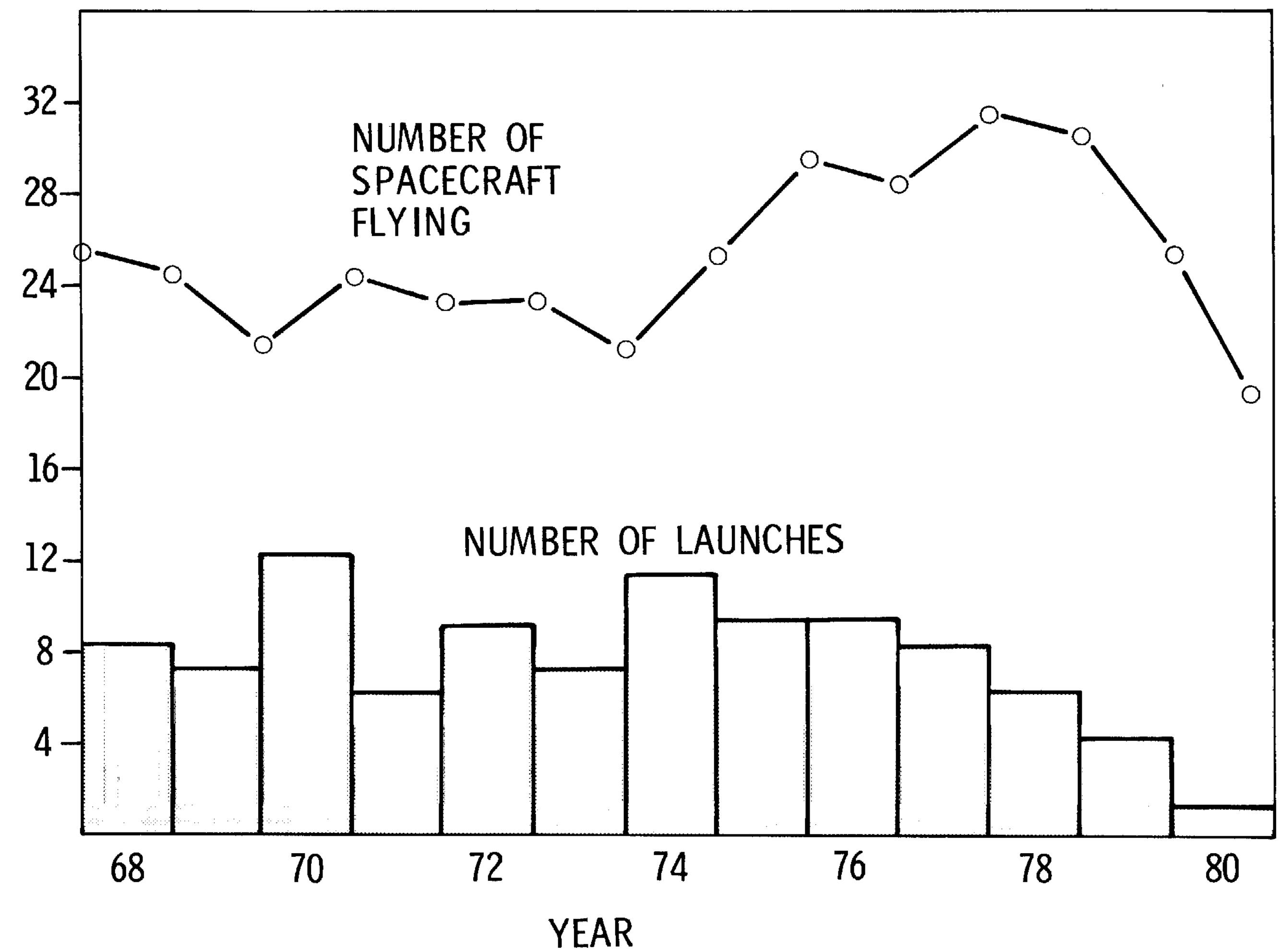

Figure 1. Projected NASA Spacecraft (Those Supported by STADAN).

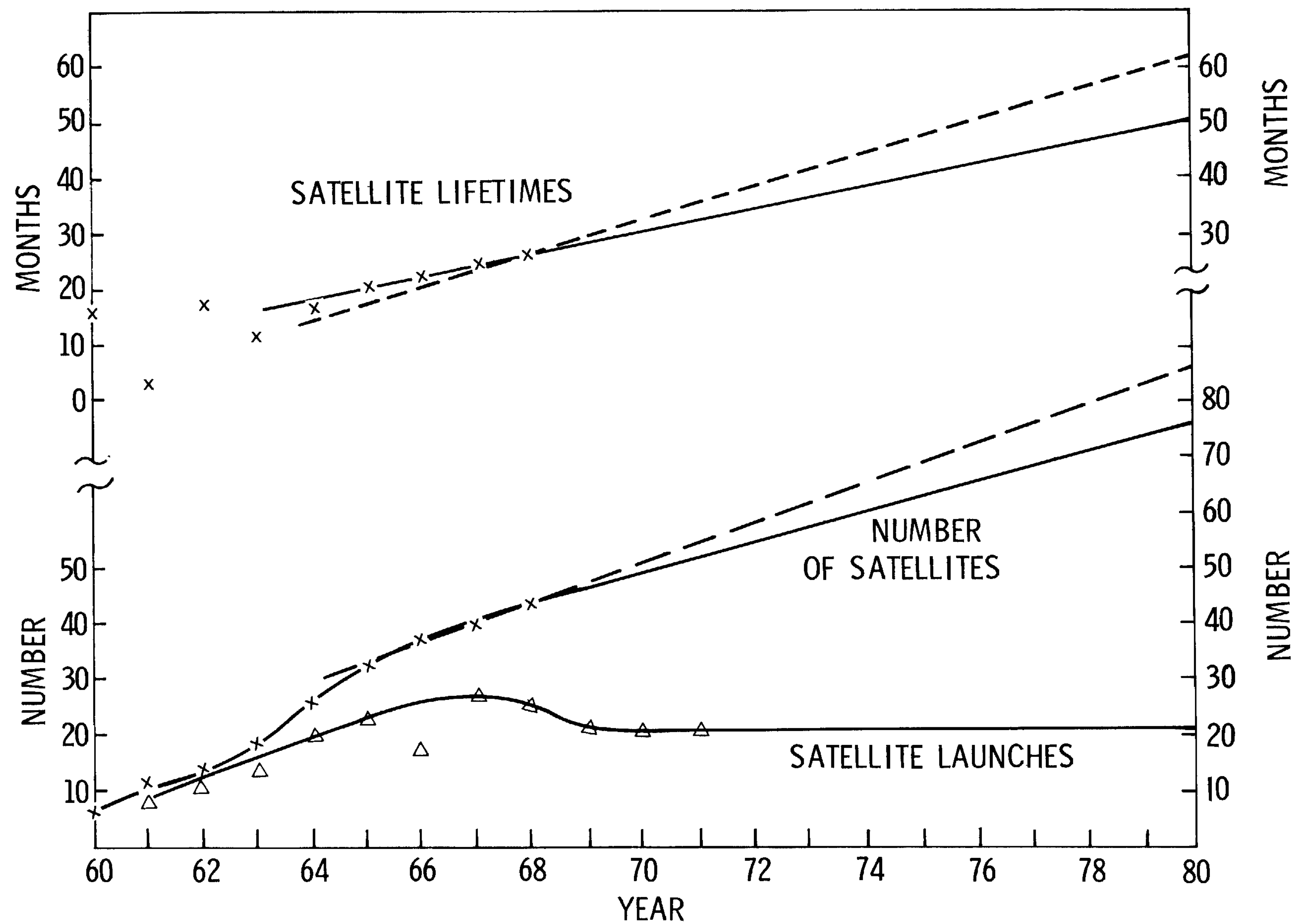

Figure 2. Predicted Number of Satellites.

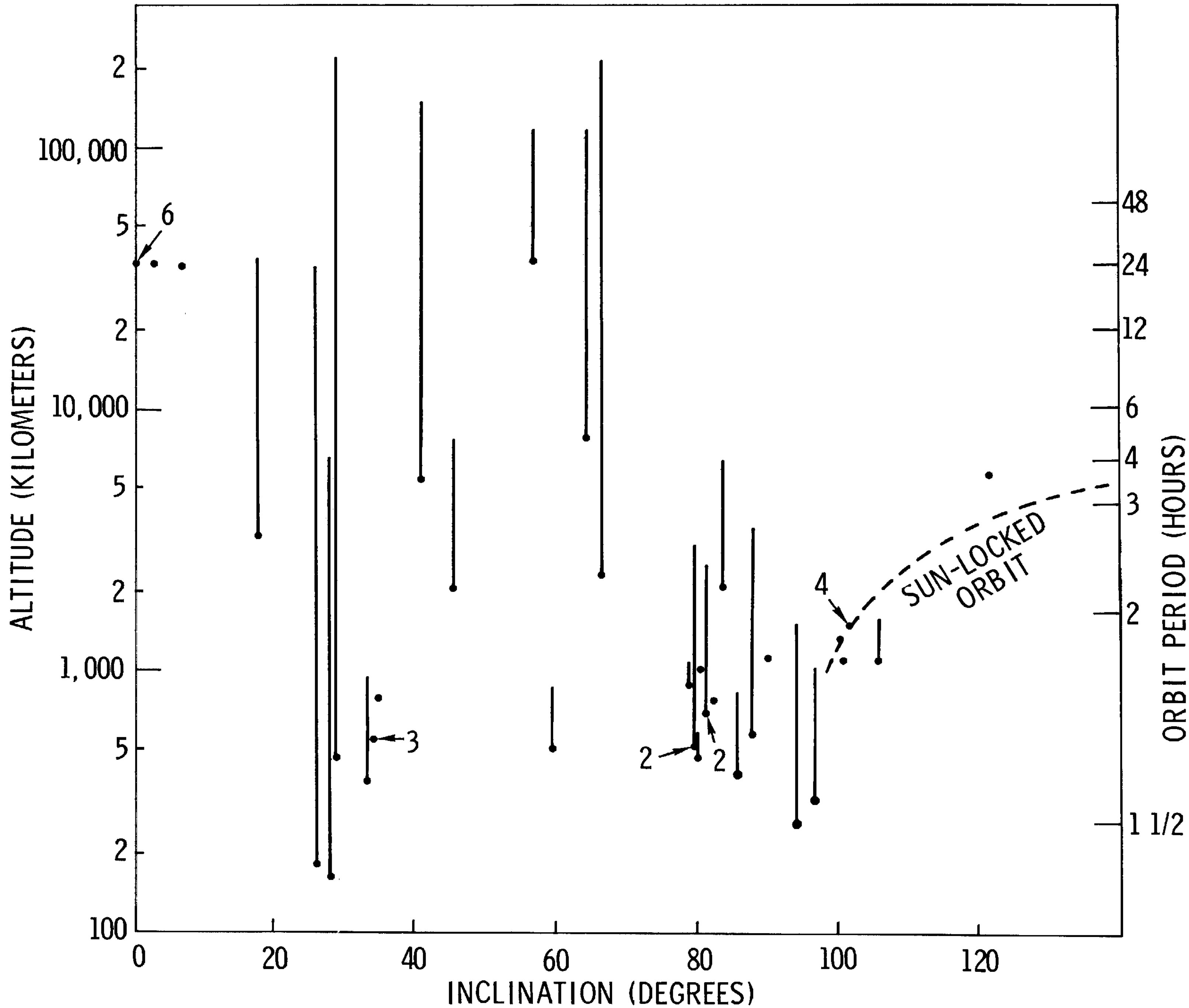

Figure 3. Current (February 1969) Distribution of 45 Earth Satellites by Altitude and Inclination.

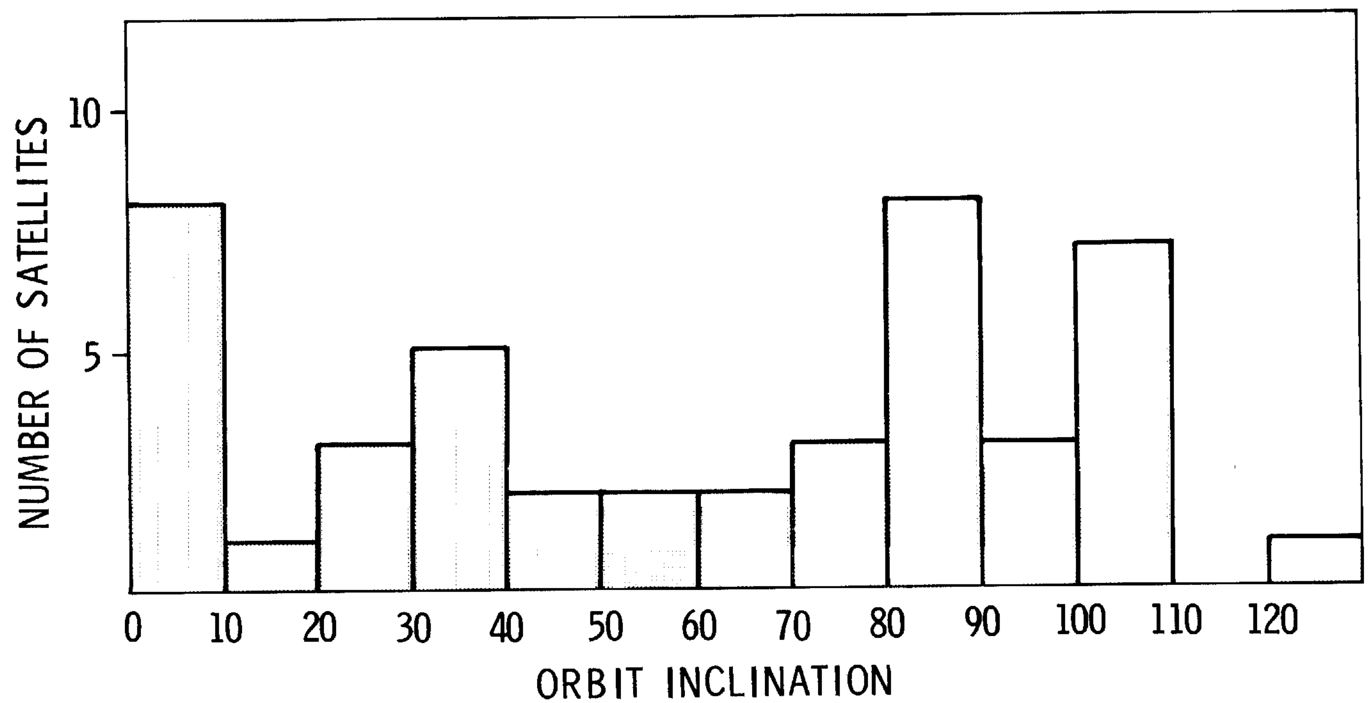

Figure 4. Current (February 1969) Distribution of 45 Orbit Inclinations.

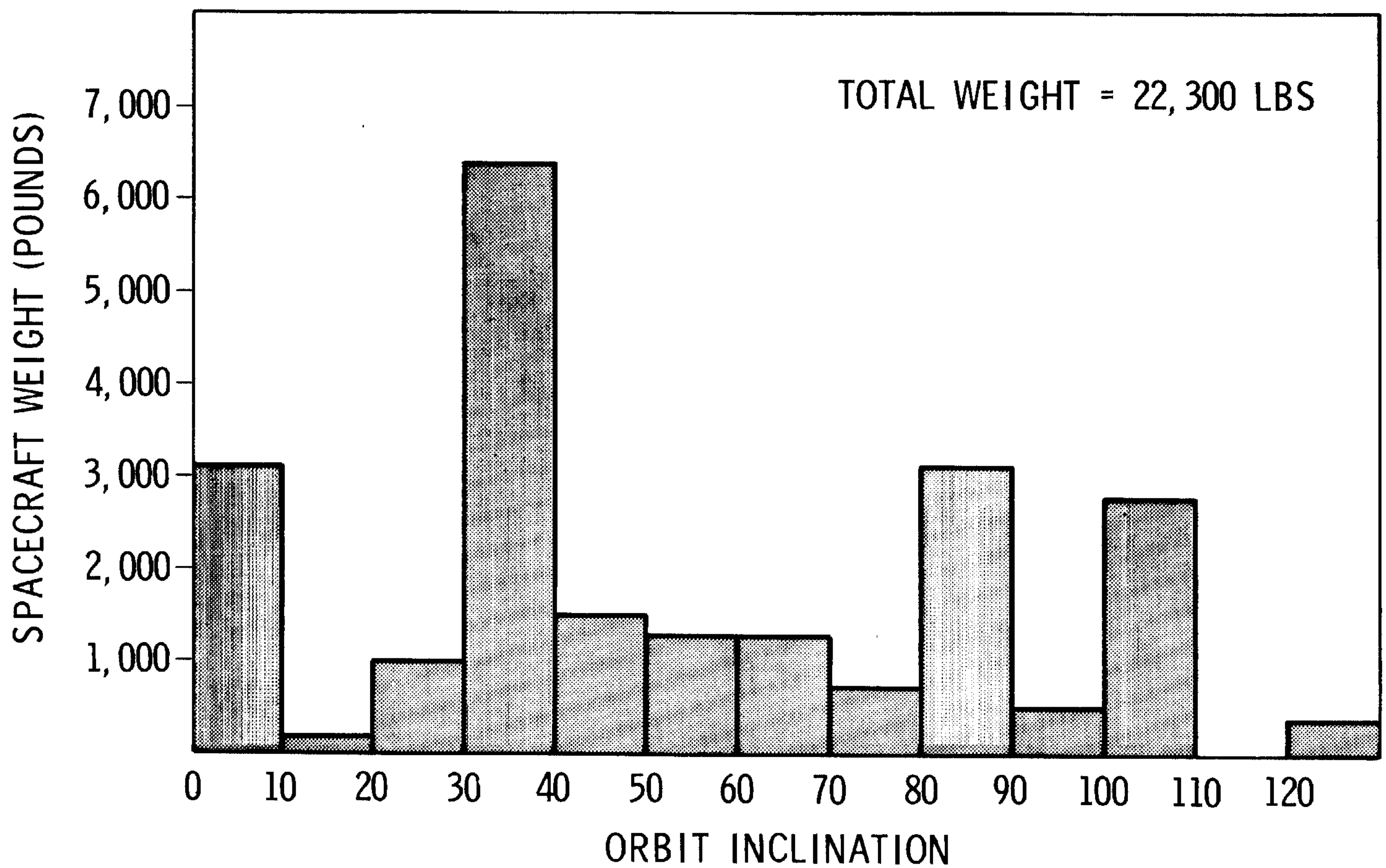

Figure 5. Current (February 1969) Distribution of Spacecraft Weight.

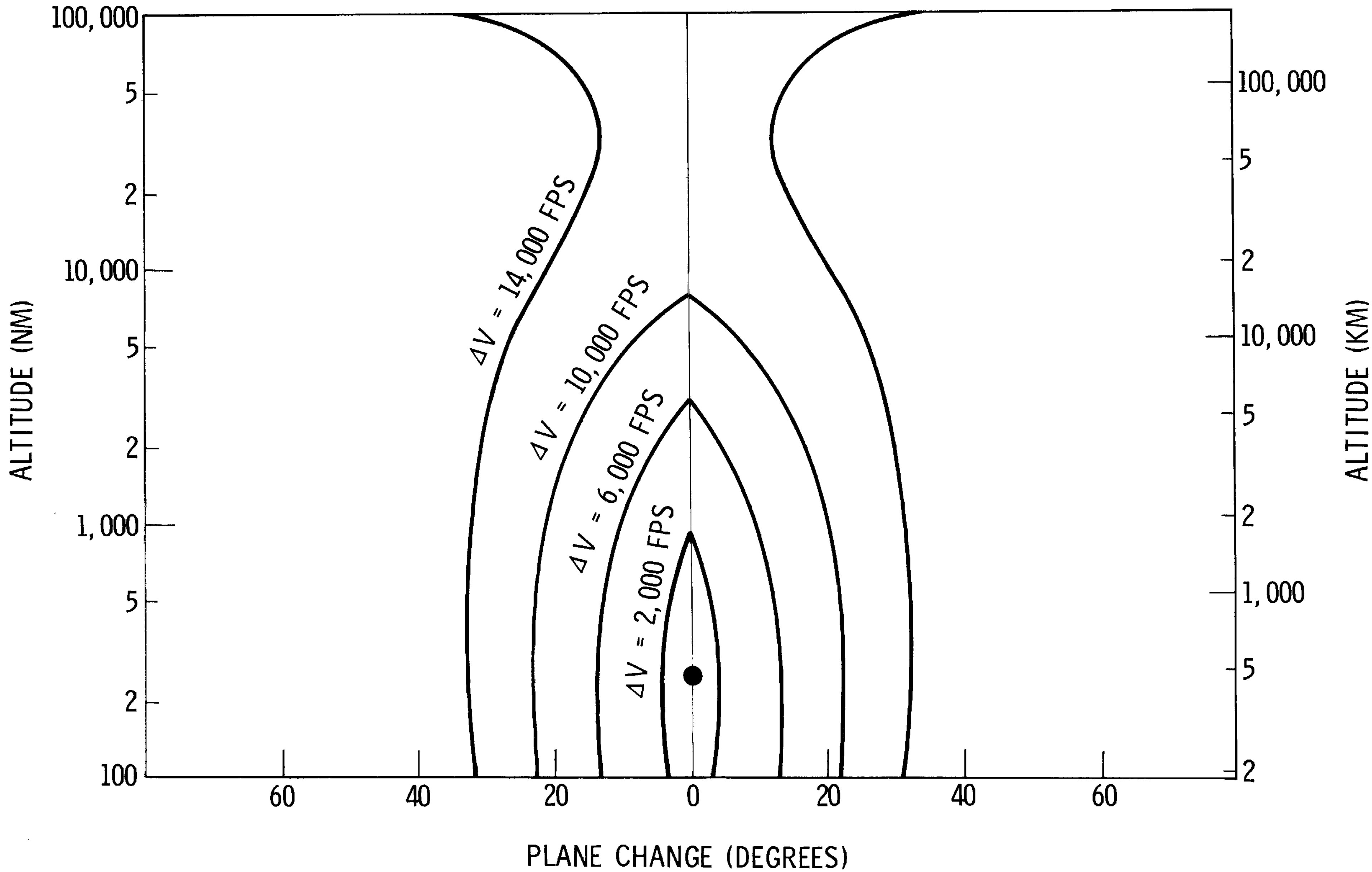

Figure 6. ΔV Contours for Impulsive Transfer to Circular Orbits from a 250 nm Circular Orbit.

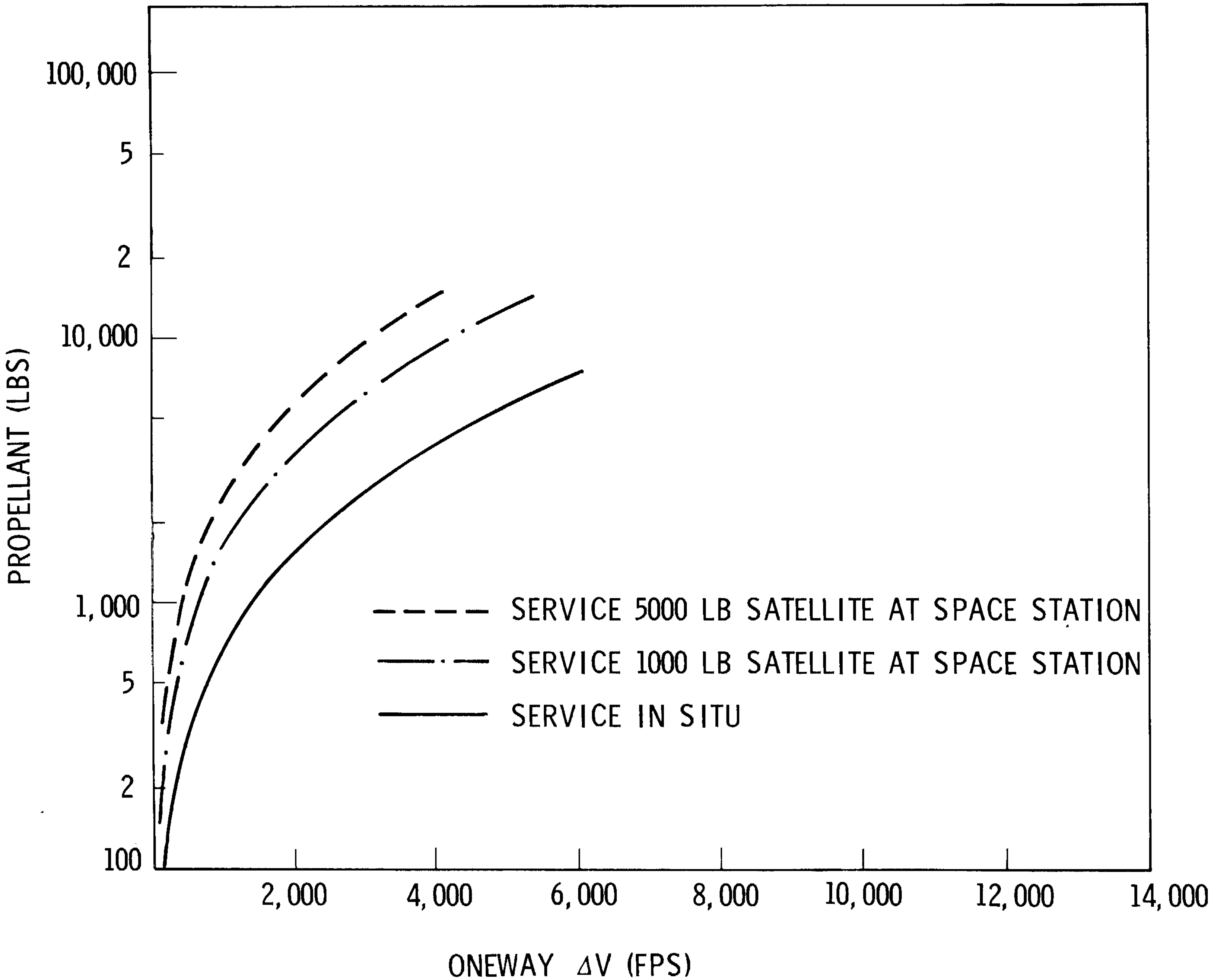

Figure 7. Servicing Propellant Requirements for Space Storable Tug.

BELLCOMM, INC.

Subject: Preliminary Survey of the Potential for Satellite Servicing - Case 730

From: H. B. Bosch

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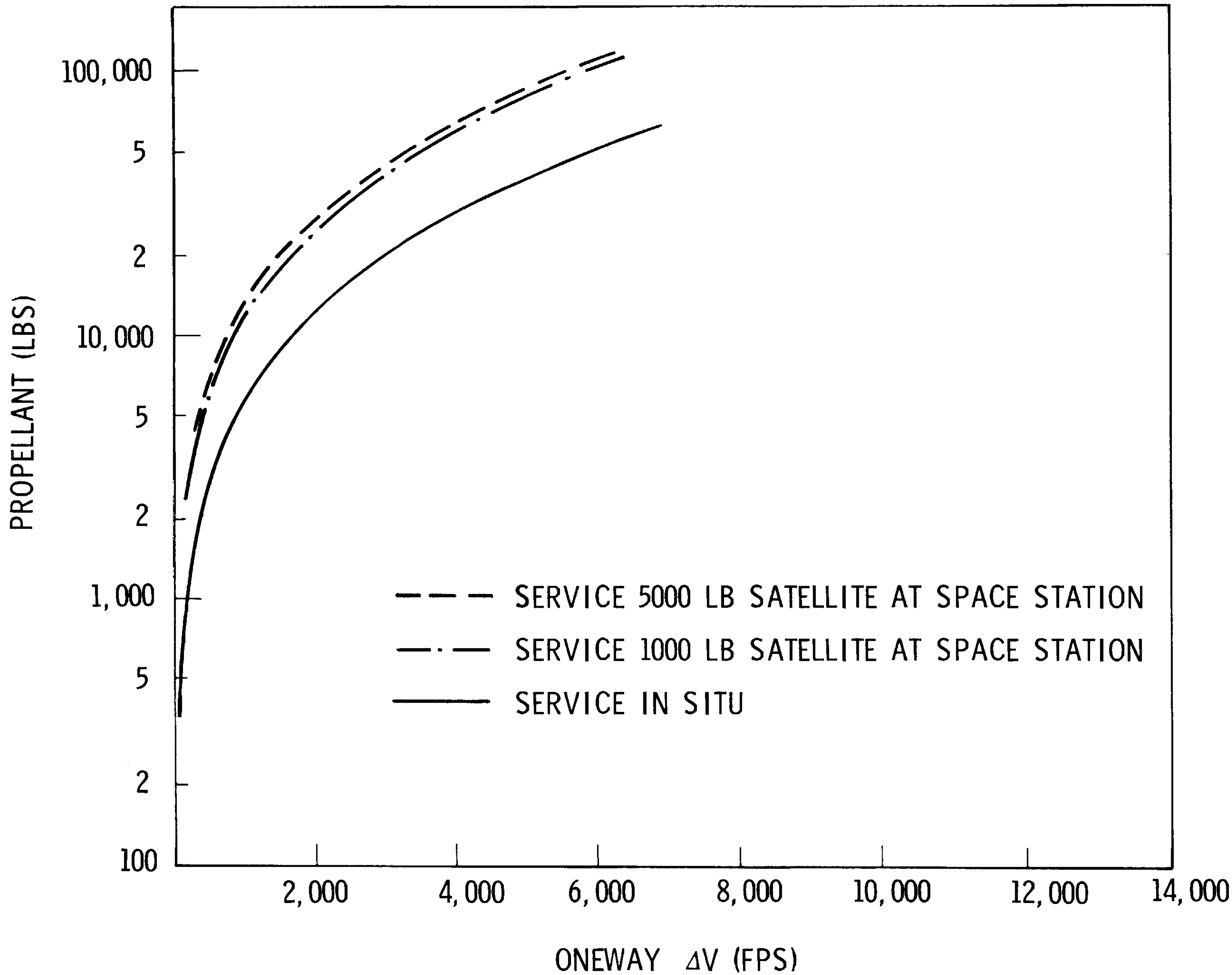

Figure 8. Servicing Propellant Requirements for Logistics Vehicle.

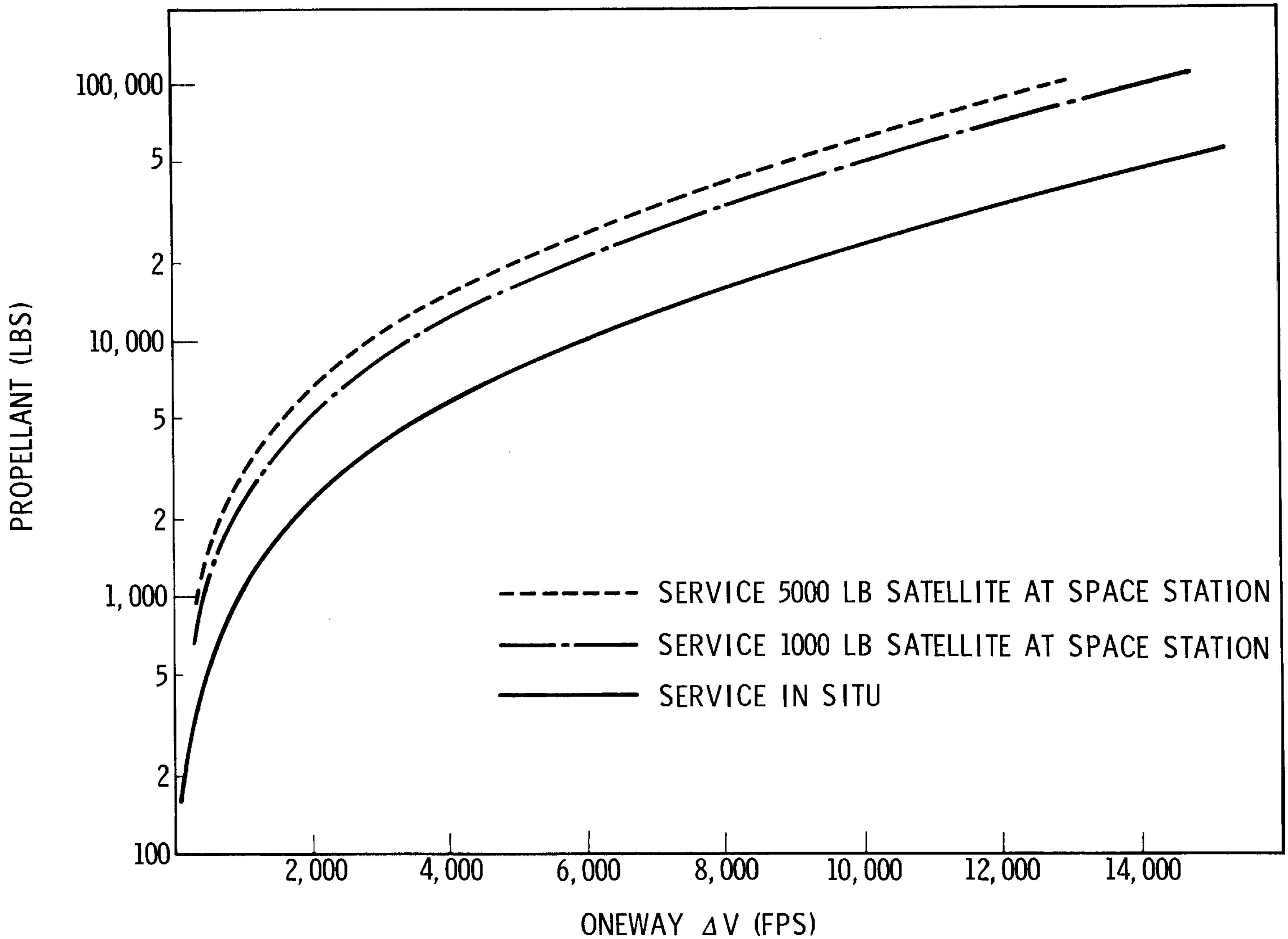

Figure 9. Servicing Propellant Requirements for Cryogenic Tug.